

Quasifree photoabsorption on neutron-proton pairs in ${}^3\text{He}^*$

J. A. Niskanen¹⁾, P. Wilhelm²⁾, and H. Arenhövel²⁾

1) Department of Theoretical Physics, Box 9, FIN-00014 University of Helsinki, Finland

2) Institut für Kernphysik, Johannes Gutenberg-Universität, D-55099 Mainz, Germany

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Abstract

Three-body photodisintegration of ${}^3\text{He}$ is calculated in the photon energy range 200 – 400 MeV assuming quasifree absorption on np pairs both in initial quasideuteron and singlet configurations. The model includes the normal nucleonic current, explicit meson exchange currents and the $\Delta(1232)$ -isobar excitation. The total cross section is increased by a factor of about 1.5 compared with free deuteron photodisintegration. Well below and above the Δ region also some spin observables differ significantly from the ones of free deuteron disintegration due to the more compressed wave function of the correlated np pairs in ${}^3\text{He}$ compared to the deuteron. The initial singlet state causes a significant change in the analyzing power A_y . These differences could presumably be seen at the conjugate angles where two-body effects are maximized and where photoreactions could complement similar pion absorption experiments.

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I. INTRODUCTION

Recently, there has been considerable experimental activity in studies of pion absorption on two or three nucleons in light nuclei [1]. These can be expected to illuminate the role of strong dynamics in few-nucleon systems and also modifications of pion absorption due to the nuclear environment. Certainly, the most direct comparison can be made between absorption on the deuteron and on correlated nucleon pairs in quasifree kinematics. The latter can be arranged by choosing the so called conjugate angles, which maximise the role of the two-nucleon mechanism, so that the reaction closely resembles the absorption on a deuteron [2–5].

Parallel to this experimental activity concentrating on cross section measurements, model predictions were published not only for cross sections but also for spin observables both in positive [6] and negative [7] pion absorption on nucleon pairs in ^3He . The former reaction suggested sensitivity of polarization observables on the quasideuteron wave function, which is not the case for the angular distribution. In the denser ^3He -nucleus short-ranged rescattering mechanisms are weighted differently than the long-ranged but oscillatory direct nucleon-nucleon overlap as compared with the free deuteron reaction. However, at least the experimental outgoing proton polarization, although measured for the quasifree kinematics, does not agree with the prediction from the quasifree model [8]. The origin of this discrepancy is not known presently, but one possibility would be the strong initial state interaction of the pion with the target nucleus. In the future, more data on quasifree absorption of positive pions are expected for both the outgoing proton polarization and also for the analyzing power iT_{11} of a polarized ^3He target [9], which might help to analyze these discrepancies in greater detail.

Contrary to the disagreement in the positive pion case, a quantitative agreement is obtained for negative pion absorption between data on a proton pair [2–5] and theoretical results [7,10]. It is interesting to note that in this case a new short-range meson exchange contribution to the two-nucleon axial current, suggested by Lee and Riska [11], has a signif-

icant effect [10]. Of course, a bound diproton does not exist as such, so a direct comparison between free and quasifree process is not possible as in the case for the absorption on a quasideuteron. However, if in the inverse process $n + p \rightarrow p + p + \pi^-$ the outgoing protons have a small relative momentum, then at this low energy the resonant 1S_0 scattering state may be considered as nearly bound and can be used with some theoretical input for a comparison with the two-body absorption in ^3He . So far, the actual experiments have been performed as $\vec{p} + n \rightarrow (p + p)_{^1S_0} + \pi^-$ but on a deuteron target [12,13] and the spin observables show little deviation from the predictions. However, in this case there is only a rather moderate dependence on the relative two-body wave function. Still, the accuracy of the experiments is sufficient in order to allow in principle to distinguish between several wave functions.

With the above somewhat confused situation in pion absorption – agreement between theory and experiment in one case, strong discrepancy in the other – one is tempted to consider another probe for the study of the pair correlations. If the source of the disagreement is, indeed, the strong initial state π -nucleus interaction, then an obvious choice would be to attempt a similar approach with an electromagnetic probe. In this case the initial state interaction between the probe and the target nucleus is negligible and one may study the quasi two-nucleon processes in a much cleaner way. Another bonus is that with different quantum numbers due to different couplings this reaction offers somewhat complementary information with respect to pion absorption.

The aim of this paper is to study explicitly to which extent observables in medium energy photodisintegration of ^3He in quasifree two-body situations depend on the initial pair wave function. To a large extent this study will be devoted to the dependence of spin variables which were predicted to be sensitive in the case of pion absorption. It may be suited for experimental tests, e.g., at the LEGS facility at Brookhaven with polarized photons [14]. Preliminary results for cross sections have been published in Ref. [15].

There is a large amount of work on photodisintegration of both the deuteron [16–20] and ^3He [21] also at intermediate energies. The model of [18,20] to be used in this paper has

described deuteron photodisintegration rather successfully in the $\Delta(1232)$ -resonance region. It is now applied to the quasifree situation with modified pair wave functions. The differences between the predictions using modified pair wave functions and those for the free deuteron case should give an idea about the trends how the experimental results may differ from the free reaction. Conversely, if the theoretical results are sensitive enough to the details of the assumed pair wave functions, the experimental differences may reveal properties of those. This approach may also allow one to estimate the importance of three-body effects once the two-body absorption is understood.

Earlier theoretical work on photodisintegration of ${}^3\text{He}$ [21] has considered various one-, two- and three-nucleon mechanisms in the excitation function of one outgoing nucleon at some particular angle. Also most experimental results have been presented in this way [22,23]. The first results with polarized photons on ${}^3\text{He}(\vec{\gamma}, p)X$ from LEGS confirm the prediction by Laget about the importance of three-nucleon effects in general on the one hand and about the existence of a quasi two-body region on the other hand, where two-body mechanisms are by far dominant [23]. However, this earlier work does not concentrate on any detailed investigations in the quasifree region, which should be possible at the right momentum and at conjugate angles appropriate to two-body absorption and will be a further subject of this paper as a complement of two-body pion absorption studies.

The only published experimental results close to our explicit two-nucleon approach are those of the kinematically complete tagged-photon experiment of the TAGX collaboration [24]. There the differential cross sections of protons and neutrons were presented. Most of the neutron cross section can be considered as arising from the absorption on a quasideuteron in ${}^3\text{He}$, and even in the proton cross section there are clear indications of a separation into active fast protons and slow spectators.

In addition to the absence of any initial state interaction, there is another significant difference in photodisintegration compared to positive pion absorption. In pion absorption the existence of a neutron-proton pair in the isovector 1S_0 state has a negligible effect because of two suppressions of important mechanisms [27]. Firstly, due to the conservation

of parity and angular momentum, the final states are spin triplets with $J \neq L$ and the $N\Delta$ admixture can never be in an S -state as in the absorption on a quasideuteron. Further, s -wave pion rescattering is restricted to the weak isospin symmetric pion-nucleon amplitude in the nucleonic isospin conserving transition ${}^1S_0 \rightarrow {}^3P_0$. In the photon case a similar suppression may be true for the Δ -dominated M1 transitions. But according to the Thomas-Reiche-Kuhn sum rule E1 transitions should be as important for the singlet as for the triplet pair. The only suppression is a statistical factor of 3 since there are $3/2$ np -pairs in the triplet state and only $1/2$ in the singlet. So, outside the Δ region also this initial state could be significant.

In the next section we discuss some details of the model, in particular the nucleon sector with a quasideuteron pair embedded in the wave function of ${}^3\text{He}$. The results are presented in Section 3 and Section 4 gives a summary and conclusions.

II. MODEL

A. Nucleon sector

The simple starting point for the ${}^3\text{He}$ ground state is to describe its spin-isospin structure with total spin projection m by the totally antisymmetric state [7]

$$|\Psi_m\rangle = \frac{1}{\sqrt{2}} \left(\left[\left[\frac{1}{2} \times \frac{1}{2} \right]^{01} \times \frac{1}{2} \right]^{\frac{1}{2}, \frac{1}{2}, \frac{1}{2}, m} - \left[\left[\frac{1}{2} \times \frac{1}{2} \right]^{10} \times \frac{1}{2} \right]^{\frac{1}{2}, \frac{1}{2}, \frac{1}{2}, m} \right) |\Psi_{space}\rangle \quad (1)$$

assuming a symmetric S -wave space part. Using Jacobi coordinates

$$\vec{r}_{ij} = \vec{r}_i - \vec{r}_j, \quad \vec{r}_k = \frac{1}{2} (\vec{r}_i + \vec{r}_j) - \vec{r}_k \quad (ijk \text{ cyclic}), \quad (2)$$

where \vec{r}_i are the individual particle coordinates, it is parametrized in the form

$$\Psi_{space}(\vec{r}_1, \vec{r}_2, \vec{r}_3) = \frac{v(r_{12})}{r_{12}} \frac{u(\rho_3)}{\rho_3} + (\text{cyclic permutations}). \quad (3)$$

The square bracket in Eq. (1) denotes the usual coupling to a good total spin and isospin state

$$\left[\frac{1}{2} \times \frac{1}{2}\right]^{TT_z, SS_z} = \sum_{\sigma_1 \sigma_2 \tau_1 \tau_2} \langle \frac{1}{2} \sigma_1 \frac{1}{2} \sigma_2 | SS_z \rangle \langle \frac{1}{2} \tau_1 \frac{1}{2} \tau_2 | TT_z \rangle \left| \frac{1}{2} \sigma_1, \frac{1}{2} \tau_1 \right\rangle \left| \frac{1}{2} \sigma_2, \frac{1}{2} \tau_2 \right\rangle. \quad (4)$$

The “quasideuteron” can be identified in the first term of Eq. (1). By writing the outermost coupling explicitly, one can exhibit separately the spin-isospin structures of the spectator and the pair. In this form, assuming the spectator to be inactive in the reaction, its role is diminished to just carrying a known amount of spin and charge without otherwise affecting the two-body reaction amplitudes. The total wave function now can be written as

$$|\Psi_m\rangle = \mathcal{A} |\psi_m\rangle \quad (5)$$

with

$$\begin{aligned} |\psi_{\pm\frac{1}{2}}\rangle &= \pm \sqrt{\frac{1}{3}} |d, \pm 1\rangle |u(p), \mp \frac{1}{2}\rangle \mp \sqrt{\frac{1}{6}} |d, 0\rangle |u(p), \pm \frac{1}{2}\rangle \\ &\quad + \sqrt{\frac{1}{6}} |s(pn)\rangle |u(p), \pm \frac{1}{2}\rangle - \sqrt{\frac{1}{3}} |s(pp)\rangle |u(n), \pm \frac{1}{2}\rangle. \end{aligned} \quad (6)$$

being antisymmetric with respect to $1 \leftrightarrow 2$ only and

$$\mathcal{A} = \frac{1}{\sqrt{3}} (1 - P_{13} - P_{23}) \quad (7)$$

to achieve a total antisymmetrization where P_{ij} denotes interchange of particles i and j . The quasideuteron wave function with the magnetic quantum number μ has been denoted by $|d, \mu\rangle$, with $|s\rangle$ correspondingly the 1S_0 isovector pair with its proton and neutron contents explicitly shown and with $|u(p/n), m_{sp}\rangle$ the spectator proton/neutron wave function with spin projection m_{sp} . Explicitly the pair wave functions read in the coordinate representation

$$\begin{aligned} \langle \vec{r} | d, \mu \rangle &= \frac{v_d(r)}{r} Y_{00}(\hat{r}) \left[\frac{1}{2} \times \frac{1}{2} \right]^{00,1\mu} \\ &\quad + \frac{w_d(r)}{r} \sum_{M_L M_S} \langle 2M_L 1M_S | 1\mu \rangle Y_{2M_L}(\hat{r}) \left[\frac{1}{2} \times \frac{1}{2} \right]^{00,1M_S} \\ \langle \vec{r} | s(pn) \rangle &= \frac{v_s(r)}{r} Y_{00}(\hat{r}) \left[\frac{1}{2} \times \frac{1}{2} \right]^{10,00}. \end{aligned} \quad (8)$$

In the form of Eq. (5), the space parts of the different pair wave functions have now no longer be assumed to be identical S -waves. In particular, the quasideuteron can be generalized to

include also the D -state in its relative correlation as shown in Eq. (8). The active pair in the last term of Eq. (6) consists of two protons and is not of concern in the present context modelling the disintegration of ${}^3\text{He}$ in terms of a quasideuteron. However, the third term is in principle indistinguishable from the quasideuteron processes and has to be considered.

Next, we want to specify the two-nucleon wave functions which have been used. A product wave function, symmetric in all the three coordinates, is a possible way to describe the spatial structure of ${}^3\text{He}$. Then the relative two-nucleon wave function could reasonably be taken as the square root of a correlation function for the pair density. This description produces the static properties quite well [28]. As correlation function we shall use the isoscalar one calculated from the Faddeev equations using the Reid soft core potential and given by Friar et al. [29]. It is supplemented by the D -state component ($P_D = 10.5\%$) in the case of the $T = 0$ quasideuteron as explained in [6]. This wave function is significantly compressed towards shorter distances as compared with the free deuteron one for which we use the one of the Bonn OBEPR potential [30]. Another possible choice for the spatial part of Ψ is a three-term parametrization in terms of basic states of the two Jacobi coordinates in different permutations given by Hajduk et al. [31]

$$\Psi_{LMlm}(\vec{r}_1, \vec{r}_2, \vec{r}_3) = \frac{v_L(r_{12})}{r_{12}} \frac{u_l(\rho_3)}{\rho_3} Y_{LM}(\hat{r}_{12}) Y_{lm}(\hat{\rho}_3) + (\text{cyclic permutations}). \quad (9)$$

In the present work, however, we need only the terms where the active nucleon pair is in the two-nucleon relative wave function v . The integrals of the other permutations may be thought to be simulated in the correlation function treatment. At least this is the case for the static properties. The tiny component of the spectator D -wave is also omitted here. Since integration over the spectator degrees of freedom is implied in any case, this omission is completely insignificant. Fig. 1 shows a comparison of the spatial wave functions used in this work.

Having in mind the photon absorption on a neutron proton pair, an appropriate final state basis is given by

$$|\Psi_{SM,m_{sp}}\rangle = \mathcal{A} \left(|\vec{P}_{np}, \phi_{SM}\rangle |\vec{p}_{sp} m_{sp}\rangle \right). \quad (10)$$

The spectator proton is described by a plane wave with momentum \vec{p}_{sp} and spin projection m_{sp} . The scattering wave function of the outgoing two fast nucleons with total momentum \vec{P}_{np} is denoted by $|\vec{P}_{np}, \phi_{SM}\rangle$ with spin S and projection M . Of course, the states of Eq. (10) can be assumed to be approximately orthogonal only in the restricted kinematic region we are interested in and which is characterized by a slow proton and a fast np pair. To calculate $|\phi_{SM}\rangle$ the Lippmann-Schwinger equation for the Bonn OBEPF potential [30] has been solved. In the isospin one states, $N\Delta$ components are taken into account by means of a coupled $NN-N\Delta$ calculation in momentum space which allows a good reproduction of the NN scattering phase shifts. In particular, the phase shift in the 1D_2 partial wave is well described [20]. This channel is of crucial importance in the Δ region because of its coupling to the $^5S_2(N\Delta)$ partial wave with vanishing angular momentum barrier. Its magnetic dipole excitation clearly dominates deuteron photodisintegration in the resonance region.

The energy of the two-nucleon final state wave function is obtained by two-body kinematic relations considering the pair to be bound by 10 MeV more than the deuteron. One half of this shift is due to the actual binding energy difference, the other half allows an average of 5 MeV kinetic energy for the spectator. It may be noted that the square of the momentum space wave function of the spectator of Ref. [31], weighted by the square of the momentum, is peaked at this energy. Also the spectator momentum distribution observed in Ref. [24] is peaked around 100 MeV/c corresponding to about 5 MeV kinetic energy. This simple description was found to simulate the exact two-nucleon energy very well for pion absorption in Ref. [7].

B. Amplitudes and observables

The 8×4 transition matrix for three-body photodisintegration of the ${}^3\text{He}$ nucleus reads

$$\delta(\vec{P}_{np} + \vec{p}_{sp} - \vec{k}) \mathcal{M}_{m_{sp}, SM, \lambda, m} = - \langle \Psi_{SM, m_{sp}} | \vec{\epsilon}_\lambda \cdot \vec{J}(\vec{k}) | \Psi_m \rangle, \quad (11)$$

where $\vec{\epsilon}_\lambda$ is the photon polarization vector, \vec{k} the photon momentum and \vec{J} the electromagnetic current which includes one-body and two-body parts

$$\vec{J} = \sum_i \vec{J}_i + \sum_{i < j} \vec{J}_{ij}. \quad (12)$$

Some more details will be given in the next section. As it stands, Eq. (11) of course also contains non-diagonal matrix elements, where the two-body current involves a nucleon which does not belong to a correlated initial or final pair. However, they are assumed to be negligible because of the short-range nature of the two-body mechanism and since we have to restrict ourself to reaction kinematics where a slow proton and a fast np pair are observed. Thus the amplitude can finally be expressed in terms of the pure two-body amplitudes which read

$$\mathcal{M}_{SM,\lambda,\mu}^d = -\langle \phi_{SM} | \vec{\epsilon}_\lambda \cdot \vec{J} | d, \mu \rangle, \quad \mathcal{M}_{SM,\lambda}^s = -\langle \phi_{SM} | \vec{\epsilon}_\lambda \cdot \vec{J} | s \rangle, \quad (13)$$

for deuteron and ${}^1S_0(np)$ photodisintegration, respectively. One finds

$$\mathcal{M}_{m_{sp},SM,\lambda,\pm\frac{1}{2}} = \left[\pm \sqrt{\frac{1}{3}} \delta_{m_{sp},\mp\frac{1}{2}} \mathcal{M}_{SM,\lambda,\pm 1}^d + \sqrt{\frac{1}{6}} \delta_{m_{sp},\pm\frac{1}{2}} (\mathcal{M}_{SM,\lambda}^s \mp \mathcal{M}_{SM,\lambda,0}^d) \right] \tilde{u}(-\vec{p}_{sp}). \quad (14)$$

The momentum space wave function \tilde{u} , reflecting the relative Fermi motion of the spectator with respect to the initial pair, will disappear after integration over the spectator momentum. Moreover, since the polarization of the spectator is not observed, the final density matrix is diagonal with respect to m_{sp} , i.e., $\tau_f = \tau \delta_{m'_{sp} m_{sp}}$, where τ describes the density matrix of the pair spin degrees. In case of an unpolarized ${}^3\text{He}$ target, Eq. (14) leads to

$$\int d^3 p_{sp} \text{tr}(\mathcal{M}^\dagger \tau \mathcal{M} \tau_i) = \frac{1}{6} \text{tr}(\mathcal{M}^{d\dagger} \tau \mathcal{M}^d \tau_\gamma) + \frac{1}{6} \text{tr}(\mathcal{M}^{s\dagger} \tau \mathcal{M}^s \tau_\gamma), \quad (15)$$

where τ_γ denotes the initial photon density matrix. This means that one ends up with an incoherent sum of the quasideuteron and the 1S_0 pair contributions. Expressed in terms of the deuteron and the singlet disintegration cross sections for unpolarized photons which are

$$\frac{d\sigma_d}{d\Omega_p} = \frac{1}{6} \text{tr}(\mathcal{M}^{d\dagger} \mathcal{M}^d), \quad \frac{d\sigma_s}{d\Omega_p} = \frac{1}{2} \text{tr}(\mathcal{M}^{s\dagger} \mathcal{M}^s), \quad (16)$$

respectively, the ${}^3\text{He}$ disintegration cross section reads

$$\frac{d\sigma_{\text{He}}}{d\Omega_p} = \frac{1}{2} \frac{d\sigma_d}{d\Omega_p} + \frac{1}{6} \frac{d\sigma_s}{d\Omega_p}. \quad (17)$$

Here it is important to note that the cross section in Eq. (17) refers to an active particle coordinate, say the active proton. It should not be mixed up with the one-arm proton cross section of the reaction ${}^3\text{He}(\gamma, p)p$ measurement. Actually it is not a directly measurable quantity, but has to be extracted from a kinematically complete experiment after an assumption on the spectator momentum distribution has been made. Also, analogously to the total cross section [26], a statistical factor $1/3$ has been inserted in Eq. (17) to account for the indistinguishability of the unobserved spectator.

For linearly polarized photons, Eq. (15) leads to the following relation for the photon asymmetry

$$\Sigma_{\text{He}} = \frac{\Sigma_d + \frac{1}{3} \frac{d\sigma_s}{d\sigma_d} \Sigma_s}{1 + \frac{1}{3} \frac{d\sigma_s}{d\sigma_d}}. \quad (18)$$

Again, the photon asymmetry refers to photon polarization parallel and perpendicular to the plane which is defined by the photon and the active proton momenta. A completely analogous expression to Eq. (18) is obtained for the polarization of the outgoing fast nucleons. Thus for unpolarized ${}^3\text{He}$ the contributions from the triplet and singlet initial pairs are decoupled. If, say, the 1S_0 pair contribution is much smaller than the quasideuteron contribution, it can be omitted in first order approximation. This would mean that the polarizations of the two fast nucleons for example are then the same for both reactions $\gamma + {}^3\text{He} \rightarrow (pn) + p_{sp}$ and $\gamma + d \rightarrow p + n$.

Considering transversely polarized ${}^3\text{He}$ the analyzing power A_y is given by

$$\begin{aligned} A_y \frac{d\sigma_{\text{He}}}{d\Omega_p} &= \int d^3 p_{sp} \frac{1}{2} \text{tr}(\mathcal{M}^\dagger \mathcal{M} \sigma_y) \\ &= \frac{\sqrt{2}}{3} \text{Im} \sum_{SM} \left[\left(\mathcal{M}_{SM,0,+1}^d \right)^* \left(\mathcal{M}_{SM,+1,+1}^d - \mathcal{M}_{SM,-1,+1}^d \right) \right. \\ &\quad \left. + \left(\mathcal{M}_{SM,+1}^s \right)^* \left(\mathcal{M}_{SM,+1,+1}^d + \mathcal{M}_{SM,-1,+1}^d \right) \right]. \end{aligned} \quad (19)$$

This is the same result as given in [27] for pion absorption on ${}^3\text{He}$ and is also the same as for photon (or pion) absorption on a free deuteron, except for the presence of the 1S_0 pair as well as different wave functions and slightly different kinematics. Finally, it may be worth noting

the reason for the preference of the Cartesian component A_y over the spherical one it_{11} of the analyzing power in comparisons of the ^3He and deuteron reactions. In the Madison convention [25] the A_y has the same expression in both cases in terms of the transition matrices, so that any differences would have a basically dynamic origin. However, the spherical quantities for the spin- $\frac{1}{2}$ and spin-1 particles would have normalizations differing by an additional factor of $\sqrt{2/3}$.

C. Electromagnetic interaction

The photoabsorption mechanisms on the two-nucleon system which have been included in the present calculation are summarized in Fig. 2. The model includes the usual one-nucleon current ($N[1]$) (Fig. 2a), which is given by the spin and the convection current. Furthermore, the spin orbit current which gives the most important relativistic contribution is also considered. Moreover, Siegert operators corresponding to the nonrelativistic one-body charge density are applied. Their use allows to take into account the dominant part of the exchange current contribution to the electric multipoles in a model independent way (see e.g. [35]). The electromagnetic interaction described up to now defines the so called normal part (N).

In case of the quasideuteron disintegration explicit static π - as well as ρ -meson exchange currents (MEC) beyond the Siegert operators are included. In the nucleonic sector shown in Fig. 2b,c, they are consistent with respect to gauge invariance to the π - and to the dominant part of ρ -exchange in the OBEPR potential as explained in detail in Ref. [36]. In the calculation of the $^1S_0(np)$ disintegration the MEC effects are incorporated via the Siegert operators only.

Of course, direct Δ excitation is the most important photoabsorption mechanism at intermediate energies. Within the $NN-N\Delta$ coupled channel approach it can be considered as a one-body contribution depicted in Fig. 2d, once the $N\Delta$ component of the wave function has been generated. We take into account the dominant magnetic dipole excitation only

using the modified $\gamma N\Delta$ coupling of Ref. [20] which led to a good description of the size and the energy dependence of the total cross section for deuteron photodisintegration in the Δ region. The two-body Δ excitation due to the exchange current shown in Fig. 2e-g is of minor importance.

It is worth noting that all the Δ -excitation mechanisms of Fig. 2d-g cannot contribute to the break-up of the $^1S_0(np)$ pair because of the isospin selection rule. Since the Δ excitation is always going along with an isovector transition, it cannot link neutron-proton isovector states having $T_z = 0$, i.e., the contributions from neutron and proton excitation cancel each other exactly. This argument is not valid any more, if the break-up of the $^1S_0(pp)$ pair would be considered.

III. RESULTS

The primary aim of this paper is to study the expected deviations of the quasifree from the free two-nucleon disintegration due to differences in the initial state wave functions as shown in Fig. 1. However, it is of interest at first to make some comments about the effect of the different mechanisms shown in Fig. 2 and discussed in Sec. 2.3. Fig. 3 presents the accumulation of these contributions at 300 MeV photon energy, just below the Δ -resonance energy which corresponds to $E_\gamma \approx 320$ MeV. All observables are presented as a function of the proton angle in the center of momentum system of the two fast final state nucleons (or of the photon and the initial nucleon pair), which is the only free variable in two-body reactions. These results are obtained using the square root of the correlation function for the initial pair wave function. The dotted curves show the purely one-nucleon current contribution and short-dashed ones the one-body part with the inclusion of two-body terms by the Siegert operators . In the long-dashed curves the normal part is further supplemented with the explicit π - and ρ -meson exchange current effects (MEC) shown in Fig. 2b,c beyond the Siegert parts. The most important individual effect is the direct Δ excitation shown in Fig. 2d, which is included in the solid curves. Furthermore, the Δ -MEC of Fig. 2e-g is

added in the solid curves, but it is of minor importance.

The dominance of the Δ isobar has been demonstrated earlier in deuteron photodisintegration [18–20], but in the present quasideuteron case the initial state wave function is significantly more compressed to shorter distances. Thus one could expect the short-range effects to be more prominent. Also the nucleonic term can obtain stronger high momentum components with the compressed wave function. So for the more condensed initial wave function both the one-nucleon and MEC as well as the isobar effects should be enhanced.

To investigate their interplay quantitatively and also for completeness, Fig. 4 presents the same observables for the true deuteron wave function and kinematics. An enhancement by a factor of three in the cross section can be attributed to the more condensed wave function. Both the explicit MEC and the isobar effects on the one hand and the nucleon current contribution on the other hand are increased, but in the latter the enhancement is stronger. Here all changes go in the same direction to increase the total cross section, but the angular distribution remains the same at this energy. The statistical factor $\frac{1}{2}$ in Eq. (17) reduces this enhancement leaving a ratio of approximately 1.5 between the cross sections of Figs. 3 and 4. Experimental evidence [22,24] indicates the ratio of this magnitude. It should be emphasized that the difference of the initial wave functions is the reason for the quasifree cross section being larger than the free one, *not* the number of quasideuteron pairs in ${}^3\text{He}$.

In the photon asymmetry Σ , the free deuteron gets relatively larger individual contributions than ${}^3\text{He}$. In both cases the explicit MEC and the isobar contribution go oppositely to the normal part resulting in virtually indistinguishable total results. The proton polarization is not changed significantly either in this energy region with the maximal Δ contribution. All results for the neutron polarization were similar to those for the proton and thus will not be shown separately. Only the analyzing power A_y has a significantly different result at this energy, partly because of the first order interference effect from the singlet state pair wave function as shown in Eq. (17).

A detailed study of the contributions from the different components of the initial pair

wave functions is presented in Fig. 5. All cross sections are normalized as contributions to $d\sigma_{\text{He}}/d\Omega_p$ in Eq. (17). The short-dashed curves show the results for the quasideuteron component alone. Large parts of the amplitudes arise from its D -state. Its omission leads to qualitative changes in the nucleonic spin observables as seen in the long-dashed curves. This can be expected because the nucleon spin orientation is totally different in the D -state than in the S -state. The separate 1S_0 contribution (also in this case the spin observables are scaled with the corresponding cross section) is also qualitatively different from the quasideuteron, but its weight is overall too small to cause any significant changes in the total observables except in A_y (solid vs. short-dashed curves). In the reaction products this initial configuration is, of course, indistinguishable. However, with different multipoles (notably E2) it can be seen separately for example in the quasifree disintegration of the diproton in ${}^3\text{He}$ [34]. It may be noted that A_y is not existing in case of the ${}^1S_0(np)$ disintegration.

Fig. 6 shows the dependence on the different models for the pair wave functions at four photon energies ranging from 220 MeV to 360 MeV. The dotted curves are the results for a free deuteron pair wave function corresponding to deuteron photodisintegration with the cross section multiplied by the factor 1/2 of Eq. (17) for comparison of the pure wave function effect, except for a slight change in the kinematics between the two reactions as explained in Sect. 2.1. The solid curves are obtained using the pair wave functions based on the correlation function of Ref. [29]. These are presumably the most realistic predictions in this work. For comparison, however, the parametrization of Ref. [31] is used to calculate the dashed curves. It is of interest to note that the wave function differences have a larger effect outside the Δ region. This was also the case in positive pion absorption on the quasideuteron [6]. There the spin observables had a clear trend in the energy dependence and the quasideuteron results crossed the free reaction results at the Δ -peak energy. At 220 MeV only the final state proton polarization is similar for the different initial state wave functions. To check the trends with increasing energy, we performed also the calculation fairly well above the Δ region at 420 MeV photon energy not shown here. The decrease of the cross section continued and also other variables continued slowly the trends of Fig.

6. Only in the case of A_y the rate of change with energy between the different models is significant at and above the Δ region. It seems that photon energies below the Δ region are the most promising to see differences arising from the different initial states in absorption on neutron-proton pairs.

To better understand the energy dependence of the observables we present in Fig. 7 the magnitudes of the leading multipole contributions to the total cross section as a function of energy compared with those of the free deuteron photodisintegration (dashed curves). Also in the quasideuteron case absorption above 200 MeV is dominated by the direct isobar contribution Fig. 2d in the magnetic dipole transitions, while below 200 MeV the electric dipole takes over. In the free reaction the Δ becomes already dominant at a somewhat lower energy resulting in a slightly deeper minimum in the cross section. It can further be seen that the ratios of the multipole strengths for the quasifree and free cases remain quite well energy independent above 100 MeV so that one would, indeed, expect a rather smooth energy dependence. The strongest energy dependence appears in the ratio $M2(qd)/M2(d)$. This multipole is strongly affected by the $N\Delta$ admixture of the 3F_3 final state. Also the strengths of all multipoles increase in going from the free to the quasifree reaction so that the qualitative similarity of the observables is understandable as far as the quasideuteron absorption is concerned. However, because of the different quantum numbers, obviously there must be more changes in the absorption on the 1S_0 pairs. As discussed in Sect. 2.3, in that case the Δ isobar cannot contribute directly, and in the corresponding curves of Fig. 7b its explicit contribution to the amplitudes has been left out also in the “free deuteron” comparison. However, the $N\Delta$ component is retained in the calculation of the wave functions. Without the isobar contribution the M1 multipole is drastically suppressed and E1 is far more prominent than in the quasideuteron and dominates the process now up to 300 MeV. The “free” reaction without the Δ would be completely dominated by E1. Also the energy dependence of the relative multipole strengths is now quite different, apparently causing the stronger energy dependence observed above in the analyzing power A_y , where the 1S_0 pair amplitude appears in first order.

It is also of interest to point out a prominent feature in the E2 multipole transition in the 1S_0 pair case. The dip around 300 MeV is due to the renormalizing effect of the strong $^5S_2(N\Delta)$ component on the $^1D_2(np)$ final state wave function, i.e., part of the two-baryon wave function, i.e., the $N\Delta$ component, is not directly contributing to the reaction. The dotted curve shows the E2 multipole contribution calculation using the two-nucleon wave function without the coupling to the isobar configurations. To our knowledge such a strong feedback from an isobar admixture on the *nucleonic* part of the wave function has not been observed elsewhere. The unique selectivity of the isospin structure is responsible for the large reduction by about a factor of two in the E2 contribution to the total cross section. It remains to check whether it can be observed in two-body photoabsorption on the pp pair in ^3He , where the E2 multipole should be far more important [34].

Finally, Fig. 8 shows a comparison to the recent experimental results of the TAGX collaboration [24]. The magnitude of the total cross section is quite reasonable for both models of the pair wave functions. For comparison, the dotted curve shows the free deuteron result without the factor 1/2 used in Fig. 6. The energy dependence below 200 MeV is not well reproduced in any of the models. It is possible that at low momentum transfers also the spectator with its Fermi motion can contribute. Also in the data the Δ peak is somewhat shifted towards lower energies as compared to the free deuteron case and the present ^3He calculations. The earlier data both in this energy region [22] and below [33] would allow a somewhat higher cross section than Ref. [24].

IV. SUMMARY AND CONCLUSIONS

We have studied photodisintegration of ^3He in a quasideuteron model where the photon is absorbed at a correlated np pair while the third nucleon merely acts as a spectator. In addition to a bound quasideuteron, we have also considered the contribution of a bound $^1S_0(np)$ pair. The final np pair interaction is completely included as well as MEC and Δ excitation. For the initial pair correlation function several models have been used. The

compression of the np correlation wave function compared to the free deuteron case enhances both short-range MEC and Δ effects and the one-body contribution as well. This nearly triples the cross section. However, the quasideuteron cross section becomes reduced by a statistical factor $1/2$ leading to an overall enhancement by about 1.5 as compared with the free reaction. Also in the relative spin observables and angular distributions there are significant changes both well below and above the Δ -resonance region. Around the resonance, the changes in the nucleonic and meson currents on one hand and in the isobar current on the other hand act in opposite directions and thus cancel each other to some extent in the relative quantities so that the ^3He results are rather similar to the free deuteron case. This insensitivity on the initial pair wave function suggests that in experiments trying to use two-body reactions to investigate these wave functions, the Δ region is not a good choice. The same conclusion has also been reached in corresponding pion absorption studies [6] where a systematic energy dependence of the change was seen. The sensitivity is far greater outside this energy region, and significant effects can be expected there.

In the present calculation the quasideuteron disintegration was by far the dominant contribution to the observables up to the Δ region, while the 1S_0 initial configuration appeared to be significant only through the first order interference term in the analyzing power A_y . However, well above this energy the Δ isobar loses its prominence and also the purely nucleonic current from the 1S_0 pair gains importance. So higher energies are more sensitive to this component. There one could also expect a rising importance of the excitation of the Roper resonance in the magnetic dipole transitions to the $^3S_1 - ^3D_1$ waves.

For the np final states both the triplet and singlet initial configurations add coherently. However, the singlet pair could be separately studied in diproton photodisintegration by mainly the $E2$ multipole transition [34]. Any of these two-body break-up studies may be within present experimental possibilities, e.g., LEGS [14] or TAGX [24]. One advantage of these two-body photoabsorption processes is that just one or two quantum states can be singled out in the initial states. It would also be interesting if bremsstrahlung experiments could be performed with the relative final state nucleon energy constrained so low that only

the S -wave would be sufficient for its description similarly to the present pion production experiments [13]. In this kind of simplified situation one could expect clean signals of different multipoles and exchange currents to be seen and distinguished.

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FIGURE CAPTIONS

Fig.1 Comparison of the different pair wave functions used in the present work: wave functions based on the correlation function of Friar et al. [29] (dashed), on the Faddeev wave function parametrization of Hajduk et al. [31] (dotted and dash-dotted in case of the 1S_0 pair), and on the Bonn OBEPR potential [30] (full).

Fig.2 Diagrammatic representation of the various photoabsorption mechanisms included in the present model.

Fig.3 Separate electromagnetic contributions to the cross section, photon asymmetry Σ , proton polarization P_y , and analyzing power A_y for $\gamma + {}^3\text{He} \rightarrow (pn) + p_{spec}$ at $k_{lab} = 300$ MeV: nucleonic one-body currents (dotted), normal part (short-dashed), and consecutively added explicit π/ρ -MEC (long-dashed) and Δ excitation (full).

Fig.4 As Fig. 3, but for the free deuteron photodisintegration reaction $\gamma + d \rightarrow p + n$.

Fig.5 Dependence of various observables for $\gamma + {}^3\text{He} \rightarrow (pn) + p_{spec}$ at $k_{lab} = 300$ MeV on the different components of the initial pair wave functions: only quasideuteron (short-dashed), only quasideuteron but without D -state and with renormalized S -state (long-dashed), only $^1S_0(np)$ pair (dotted), and complete calculation (full). All components are based on the correlation function of Ref. [29].

Fig.6 Dependence of various observables for $\gamma + {}^3\text{He} \rightarrow (pn) + p_{spec}$ at $k_{lab} = 220\text{--}360$ MeV on the model for the initial pair wave functions: the wave function based on the correlation function of Ref. [29] (full), on the Faddeev wave function parametrization of Ref. [31] (dashed), and the free deuteron OBEPR wave function with the cross section multiplied by a factor $\frac{1}{2}$ (dotted).

Fig.7 The full curves show the leading multipole contributions to the total photodisintegration cross sections for the quasideuteron σ_d (a) and the singlet np pair σ_s (b) as in Eq. (17) (without the factors $1/2$ and $1/6$) in comparison with the free deuteron

photodisintegration (dashed curves). The dotted curve in (b) is explained in the text.

In (b) the “deuteron” results contain only the normal part.

Fig.8 The total cross section for two-body photoabsorption on np pairs in ${}^3\text{He}$. The curves as in Fig. 6 except that the deuteron cross section is not multiplied by $1/2$. The data are from Ref. [24].

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